ESTCP
Cost and Performance Report

(MR-200807-200909)

Hand-held EMI Sensor for Cued UXO Discrimination
Man-Portable EMI Array for UXO Detection and Discrimination

March 2012

ENVIRONMENTAL SECURITY
TECHNOLOGY CERTIFICATION PROGRAM

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ACRONYMS AND ABBREVIATIONS

AOL	Advanced Ordnance Locator
APG	Aberdeen Proving Ground
ATC	Aberdeen Test Center
E	discrimination efficiency
EMI	electromagnetic induction
ESTCP	Environmental Security Technology Certification Program
FUDS	formerly used defense sites
GPS	Global Positioning System
HE	high explosive
HH	hand-held
IVS	instrument verification strip
MP	man-portable
MR	Munitions Response
MTADS	Multisensor Towed Array Detection System
NRL	Naval Research Laboratory
PI	Principal Investigator
QC	quality control
Rx	receiver
Rfp	false positive rejection rate
SAIC	Science Applications International Corporation
SAINT	Small-Area Inertial Navigation Tracking
SERDP	Strategic Environmental Research and Development Program
SLO	San Luis Obispo
SNR	signal-to-noise ratio
TEM	transient electromagnetic
TEMTADS	Time-Domain Electromagnetic MTADS
Tx	transmitter
USACE	U.S. Army Corps of Engineers
UXO	unexploded ordnance

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ACKNOWLEDGEMENTS

This work was done as part of the Naval Research Laboratory's (NRL) Environmental Security Technology Certification Program (ESTCP)-funded projects Munitions Response (MR)-200807 and MR-200909. The work was done in collaboration with Nova Research, Science Applications International Corporation (SAIC), and G&G Sciences. Dave George of G&G Sciences was responsible for the development of the electromagnetic induction (EMI) sensor technology on which the Time-Domain Electromagnetic Multisensor Towed Array Detection System (TEMTADS) arrays are built. Tom Bell of SAIC, Dan Steinhurst and Glenn Harbaugh of Nova Research, and Barry Mathieu of Berry Design collaborated on the design of the integrated MP cart and hand-held sensor system. Dan Steinhurst and Barry Mathieu were responsible for the design and construction of back-pack mountable electronics package for the sensor systems. Jim Kingdon, Bruce Barrow, Jonathan Miller, and Dean Keiswetter of SAIC were also involved in the modeling and analysis of the resultant data.

We would like to thank Rick Fling of the Aberdeen Test Center for his invaluable assistance with both demonstrations at the Aberdeen Proving Ground (APG) Standardized Unexploded Ordnance (UXO) test site. The authors would also like to thank Brian Ambrose of DuPont for providing access to the Remington Woods, CT, site as part of their ongoing remediation efforts and to Jeffrey Kronick of URS Corporation for onsite support at the Remington Woods site. Andrew Schwartz of the U.S. Army Corps of Engineers (USACE), Huntsville provided the funding for the Dalecarlia Woods, Washington, DC, site under the USACE Innovative Technology Program. The USACE Baltimore District and the Shaw Group provided site access and support for the Dalecarlia Woods, Washington, DC, site.

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1.0 EXECUTIVE SUMMARY

1.1 BACKGROUND

The Chemistry Division of the Naval Research Laboratory (NRL) has participated in several programs funded by the Strategic Environmental Research and Development Program (SERDP) and the Environmental Security Technology Certification Program (ESTCP) whose goal has been to enhance the classification ability of the Multisensor Towed Array Detection System (MTADS). The NRL Time-Domain Electromagnetic MTADS (TEMTADS) 5x5 array incorporates an advanced electromagnetic induction (EMI) sensor specifically designed for unexploded ordnance (UXO) classification. The system was designed to incorporate the most successful to date survey strategy: a static, gridded survey where the relative position and orientation of the sensors are precisely known with the coverage efficiencies of a vehicular-towed system.

Based on the success of the TEMTADS, NRL undertook efforts to transition this technology to smaller, man-portable (MP) and hand-held (HH) systems for deployment in more confined terrains. These Adjuncts of the NRL TEMTADS sensor are based on the transient electromagnetic (TEM) induction sensor technology that was developed under ESTCP project Munitions Response (MR)-200601, EMI Array for Cued UXO Discrimination. The MP system was constructed as a 2x2 array of the sensors developed for the original TEMTADS. For the HH sensor, a single, coaxial transmitter (Tx)/receiver (Rx) coil pair was developed to capture the performance of the original sensor while made rugged enough for hand-held use in the field. The required data diversity for the HH sensor comes from making a series of measurements over the target using a physical template for precise relative geolocation. Both systems are designed to be deployable in increasingly inaccessible areas where vehicle-towed sensor arrays cannot be used.

1.2 OBJECTIVES OF THE DEMONSTRATION

The objective of these demonstrations was to validate the performance of the two TEMTADS Adjunct platforms through blind testing at prepared and live sites. The systems were evaluated in terms of both classification performance (e.g., false alarm rejection) and appropriateness for fielding (i.e., production rate, usability, etc.).

1.3 DEMONSTRATION RESULTS

Demonstrations of these systems have been conducted at our test facility at Blossom Point, MD; at the UXO Standardized Test Site at Aberdeen Proving Ground (APG); and at live sites in Bridgeport, CT, and Washington, DC. These sites offer a range of UXO sizes and types along with a selection of munitions-related scrap and cultural clutter. The results of these demonstrations are discussed in terms of classification performance and production rate.

For the MP system, the APG results indicated that the inversion performance of the system was not comparable to that of the full TEMTADS 5x5 array for lower signal-to-noise ratio (SNR) targets due to the limits of the smaller data set (fewer looks at the target). The results of the live site demonstrations supported the conclusions drawn after the APG demonstration.

Revision of the sensor technology was indicated for the MP system to collect sufficient data over an anomaly. A modified version of the TEMTADS EMI sensor was designed and built, replacing the single, vertical-axes Rx loops of the original coils with three-axis Rx cubes. The new sensor elements were designed to have the same form factor as the originals, aiding in system integration.

The HH sensor was designed for use in extremely limiting terrain and for integration with unique positioning technologies. The APG results for the HH sensor indicated that the inversion performance of the system using a 36-point observation grid was comparable to that of the full TEMTADS 5x5 array.

1.4 IMPLEMENTATION ISSUES

The goal of these projects was to design and field units more amenable to operation in more confined terrain and topology. This was to be accomplished by implementing MP and hand-held configurations with the same UXO classification performance as the larger, vehicle-towed NRL TEMADS. The MP configurations could also be adapted for vehicle-towed configurations using smaller, simpler tow vehicles. A second goal was to transition these technologies from being research prototypes to being usable in the industrial community where appropriate. The mechanics of collecting classification-grade EMI data with these systems has been shown to be fairly routine in the research community. As part of the ESTCP Munitions Response Live Site Demonstrations, industrial partners will be exposed to the MP system and the associated data collection and processing procedures. The success of this effort will be evaluated as an ongoing part of the Live Site Demonstrations. Analysis of data from these systems remains somewhat of a specialty, requiring specific software and knowledge to proficiently conduct. The successful transition of the TEMTADS 5x5 array data quality control (QC)/analysis process to the Geosoft Oasis montaj environment provides a clear pathway for resolving these issues. A final implementation issue is that a clear path to making the TEMTADS Adjuncts commercially available has not been identified yet. Discussions with various groups along these lines are ongoing.

2.0 INTRODUCTION

2.1 BACKGROUND

Unexploded ordnance (UXO) contamination at former and current Department of Defense sites is an extensive problem. Site characterization and remediation activities conducted with the current state-of-the-art technologies at these sites often yield unsatisfactory results and are extremely expensive to implement. This is due in part to the inability of current technology to distinguish between UXO and nonhazardous items. Newly emerging electromagnetic induction (EMI) sensor technologies offer the ability to robustly distinguish between these two classes of objects. Early versions of these systems have tended to be large and designed for towed operation on open fields with good sky view to provide the necessary quality of geolocation information. The objective of ESTCP projects MR-200807 and MR-200909 was to demonstrate sensor arrays that are capable of reliably retaining the performance of one of these new technologies in a form suitable for use in rugged terrain and other environments where mobility and the viability of traditional positioning technologies are limited. The systems demonstrated in both projects are based on the transient electromagnetic (TEM) induction sensor technology that was developed under ESTCP project MR-200601.

2.2 OBJECTIVES OF THE PROJECTS

The objective of these ESTCP-funded NRL projects was to validate new UXO classification technologies through a series of blind test demonstrations. Both sensor technologies were demonstrated at the APG Standardized UXO Test Site. The TEMTADS MP 2x2 Cart (MP system) was also demonstrated at the DuPont Remington Woods, CT, site several times during development as part of an ongoing classification-based UXO remediation effort. The MP system array conducted a brief, exploratory demonstration at the Dalecarlia Woods site within the Spring Valley, Washington, DC, formerly used defense site (FUDS) with sponsorship from the U.S. Army Corps of Engineers (USACE), Huntsville through their Innovative Technologies Program.

2.3 REGULATORY DRIVERS

Stakeholder acceptance of the use of classification techniques on real sites will require demonstration that these techniques can be deployed efficiently and with high probability of discrimination. The first step in this process was to demonstrate acceptable performance on synthetic test sites such as that at Aberdeen. As a second step, demonstration in more real-world scenarios is required. Further demonstration at live sites with more extensive ground-truth validation will further facilitate regulatory acceptance of the UXO classification technology and methodology.

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3.0 TECHNOLOGY

3.1 TECHNOLOGY DESCRIPTION

3.1.1 EMI Sensors

Two types of sensors are discussed in this report. The first is the EMI sensor developed for the NRL TEMTADS 5x5 array under ESTCP project MR-200601 and described in the next paragraph. The second is the TEMTADS/3D sensor in which the same Tx coil is used but the Rx coil is replaced by an 8 cm, 3-component cube Rx that was first developed by G&G Sciences under a Navy-funded project known as the Advanced Ordnance Locator (AOL). We have adopted systems made from multiple copies of these sensors, assembled in a variety of array configurations. We also made minor modifications to the control and data acquisition computer to make it compatible with our deployment schemes.

A photograph of a standard TEMTADS sensor element (as used in the MR-200601 array) is shown under construction in the left panel of Figure 1. The Tx coil is wound around the outer portion of the form and measures 35 cm on a side. The 25 cm per side, square Rx coil is wound around the inner part of the form which is re-inserted into the outer portion with the vertical-axis Rx coil in place. An assembled sensor with the top and bottom caps used to locate the sensor in the array is shown in the right panel of Figure 1.

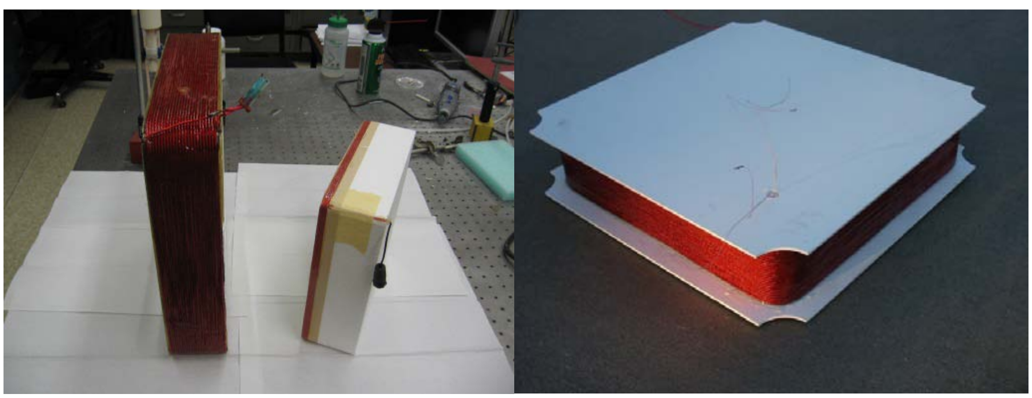

Figure 1. Standard TEMTADS EMI sensor prior to assembly (left panel) and the assembled sensor with end caps attached (right panel).

Decay data are collected with a 500 kHz sample rate until 25 ms after turn-off of the excitation pulse. A raw decay consists of 12,500 points, too many to be used practically. These raw decay measurements are grouped into 122 logarithmically spaced “gates” with center times ranging from 25 μs to 24.375 ms with 5% widths, and the binned values are saved to disk.

3.1.2 TEMTADS Hand-Held EMI Sensor

For the TEMTADS hand-held sensor, a new configuration of the TEMTADS EMI sensor was developed that is rugged, weather-proof, and designed with the needs of a hand-held instrument in mind. The sensor includes a 35 cm diameter Tx coil and an inner, 25 cm diameter Rx coil.

The assembled coil is significantly thinner than the TEMTADS sensor (2 versus 8 cm) and is designed with a clear center aperture that can be fitted with a variety of alignment fixtures. Shown in Figure 2 is a simple crosshair arrangement made from clear acrylic.

Figure 2. Construction details of the TEMTADS hand-held sensor (left panel) and the assembled sensor (right panel).

3.1.3 EMI Sensor with Tri-Axial Receiver Cubes

After demonstration of the MP system at the APG Standardized UXO Test Site in August, 2010 [1], revision of the sensor technology was indicated for the MP system to collect sufficient data over an anomaly. A modified version of the sensor element was designed and built, replacing the single, vertical-axis Rx coil of the original sensor with a three-axis Rx cube. These Rx cubes are similar in design to those used in the second-generation AOL and the Geometrics MetalMapper (ESTCP MR-200603) system with dimensions of 8 cm rather than 10 cm. The Cold Regions Research and Engineering Laboratory MPV2 system (ESTCP MR-201005) uses an array of five identical Rx cubes and a circular Tx coil. The new sensor elements are designed to have the same form factor as the originals, aiding in system integration. A standard, 10 cm MetalMapper Rx cube is shown in Figure 3 (left) A new coil under construction is shown in Figure 3 (right).

3.2 ADVANTAGES AND LIMITATIONS OF THE TECHNOLOGY

The original TEMTADS 5x5 array was designed to combine the data advantages of a gridded survey with the coverage efficiencies of a vehicular system. The MP system was designed to offer similar production rates in difficult terrain and treed areas that the TEMTADS 5x5 array cannot access.

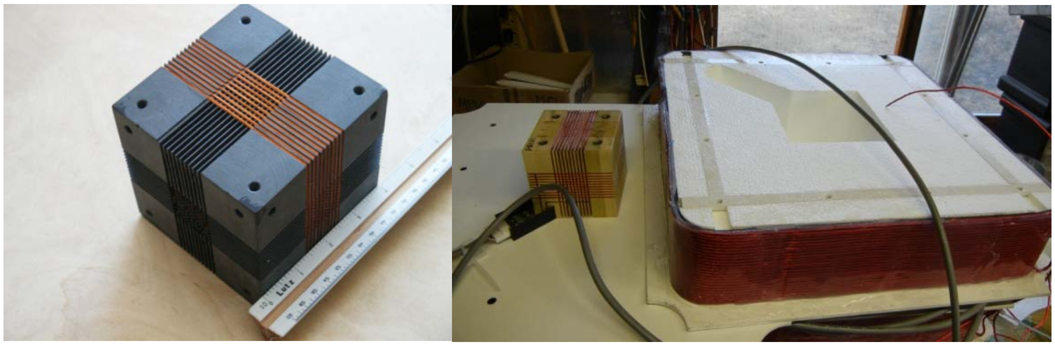

Figure 3. MetalMapper tri-axial receiver cube (left) and TEMTADS/3D EMI sensor with 3 axis receiver under construction (right).

With the upgraded EMI sensors, which incorporate the tri-axial Rx cubes, similar performance can be achieved with similar classification-grade data quality.

The MP array is 80 cm x 80 cm square and mounted on an MP cart. Terrain where the vegetation or topography interferes with passage of a cart of that size will not be amenable to the use of the system. For increasingly difficult survey conditions, the HH system allows for the data set to be built up one monostatic element at a time for flexible data collection geometries. As only monostatic measurements can be made with the HH, significantly more measurements are necessary, reducing the production rate.

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4.0 PERFORMANCE ASSESSMENT

The performance objectives for the MP system and the HH sensor at the APG demonstrations are summarized in Table 1. The results for each criterion are subsequently discussed in the following sections. For the Remington Woods and Dalecarlia Woods demonstrations, the MP system was invited to participate in ongoing remediation efforts without formal demonstration plans. Further details can be found in the combined final report for both systems [2].

Performance objectives for the demonstrations are given as a basis for the evaluation of the performance and costs of the demonstrated technologies. Since these are classification technologies, the performance objectives focus on the second step of the UXO remediation problem—that of target classification as UXO, clutter, etc. We assume that the anomalies from all targets of interest have been detected and have been included on the target list.

4.1 CORRECT CLASSIFICATION AND REDUCTION OF FALSE ALARMS

4.1.1 Correct Classification of Targets of Interest

This is one of the two primary measures of the classification value of the data collected by these sensor systems. By collecting high-quality, precisely relatively located data, it should be possible to discriminate munitions from scrap and frag with some efficiency. We expected to properly classify a large percentage of the seeded munitions items.

Table 1. Performance results for this demonstration.

Performance Objective	Metric	Data Required	Success Criteria	Success? (Yes/No)
Quantitative Performance Objectives				
Correct classification of targets of interest	Number of targets of interest identified	• Prioritized dig list • Scoring report from APG	95% correct identification of all targets of interest	HH – Yes MP – No
Reduction of false alarms	Number of false alarms eliminated	• Prioritized dig list • Scoring report from APG	Reduction of false alarms by 50% or more with 95% correct identification of munitions	HH – Yes MP – No
Cued production rate	Number of cued targets investigated per day	Log of field work	HH - 50/day MP - 200/day	HH – Yes MP – Yes
Analysis time	Average time required for inversion and classification	Log of analysis work	15 min/target	HH – Yes MP – Yes
Qualitative Performance Objective				
Ease of use	System can be used in the field without significant issues	Team feedback	Field team has no significant issues to report	HH – Yes MP – Yes
Reliability and robustness	• Number of operational hours recorded per day • Number of significant technical issues	• Field logs of operational hours per day • Field logs of significant technical issues	• ≥6 hour/day • ≤1 significant technical issue per day	HH – Yes MP – Yes

4.1.1.1 Metric

At a seeded test site such as the APG Standardized UXO Test Site, the metric for classification efficiency is straightforward. We prepared a ranked dig list from the survey data with a UXO/clutter decision for each blind grid cell and for each location in the indirect fire area that the MP system investigated. Aberdeen Test Center (ATC) personnel used their automated scoring algorithms to assess our results.

4.1.1.2 Data Requirements

The identification of most of the items in the test field is known to the test site operators. Our ranked dig lists were the input for this metric and ATC's standard scoring was the output.

4.1.1.3 Success Criteria

The objective was considered to be met for each demonstration if more than 95% of the seeded munitions items were correctly classified.

4.1.2 Objective: Reduction of False Alarms

This is the second of the two primary measures of the classification value of the data collected by these technologies. By collecting high-quality, precisely relatively located data, it should be possible to discriminate munitions from scrap and frag with some efficiency. We expected to properly classify a large percentage of the clutter as such.

4.1.2.1 Metric

At a seeded test site such as the APG Standardized UXO Test Site, the metric for false alarm elimination is straightforward. We prepared a ranked dig list from the survey data with a UXO/clutter decision for each blind grid cell and for each location in the indirect fire area that the MP system investigated. ATC personnel used their automated scoring algorithms to assess our results.

4.1.2.2 Data Requirements

The identification of most of the items in the test field is known to the test site operators. Our ranked dig lists were the input for this metric and ATC's standard scoring was the output.

4.1.2.3 Success Criteria

The objective was considered met if more than 50% of the non-munitions items were labeled as no-dig while retaining 95% of the munitions items on the dig list.

4.1.3 Results

These objectives were successfully met for the HH sensor and partially met for the MP system. The scoring reports for these demonstrations are found in References 3 and 4. Further details of the results are available in Reference 2. The HH sensor surveyed anomalies from the union of

the TEMTADS and the Small-Area Inertial Navigation Tracking (SAINT) target lists for the blind grid area. The MP system surveyed the same anomalies in the blind grid and indirect fire areas surveyed during the TEMTADS 5x5 array demonstration.

Discrimination efficiency (E) and false positive rejection rate (Rfp) measure the effectiveness of the discrimination stage processing. Efficiency measures the fraction of detected munitions retained after discrimination, while the rejection rate measures the fraction of false alarms rejected. The measures are defined relative to the number of munitions items or the number of clutter items that were actually detected by the sensor.

For the HH sensor, this objective was successfully met, with 99% of emplaced munitions items detected at the operating point with a corresponding false positive rejection rate of 93% [3]. The MP system came very close to meeting this objective [4]. 97% of the emplaced munitions were correctly classified at our selected operating point, with a corresponding false positive rejection rate of 53%. In the indirect fire area, 94% of the emplaced munitions were correctly classified, with a corresponding false positive rejection rate of 54%. For reference, the TEMTADS 5x5 array results [5] for the blind grid were 99% of emplaced munitions items detected at the operating point with a corresponding false positive rejection rate of 99%. For the indirect fire area, the percentages were 98% and 92%, respectively.

4.2 OBJECTIVE: CUED PRODUCTION RATE

Even if the performance of the technologies on the metrics above was satisfactory, economic metrics remain to be considered. Survey efficiency is the metric that was tracked in these demonstrations.

4.2.1 Metric

For cued data collection, the metric is the number of anomalies investigated per day during each demonstration. Combined with the daily operating cost of the technology, these values give the per-anomaly cost of operating each technology.

4.2.2 Data Requirements

Productivity was determined from a review of the demonstration field logs.

4.2.3 Success Criteria

Given the cued data-collection methodology used for these demonstrations, this objective was considered successfully met if the production rates were at least 50 and 200 anomalies per day for the HH sensor and the MP system, respectively.

4.2.4 Results

This objective was successfully met for both demonstrated systems. For the HH sensor, 404 target measurements were made over the course of 6 field days for an average of 67.3 targets/day. For the MP system, 1073 target measurements were made over the course of 4 field

days for an average of 268.3 targets/day. The average production rate for the 3 full days of work was 353 targets/day.

4.3 OBJECTIVE: ANALYSIS TIME

Another component of demonstration costs was the amount of analyst time required for data analysis. We tracked the near-real-time analysis time for these demonstrations.

4.3.1 Metric

The time required for inversion and classification per anomaly was the metric for this objective.

4.3.2 Data Requirements

Analysis time was determined from a review of the data analysis logs.

4.3.3 Success Criteria

Since these were the first formal demonstrations of these technologies, the objective was considered successfully met if the average inversion and classification time was less than 15 min per anomaly.

4.3.4 Results

This objective was successfully met. For the HH sensor, on average 10 min per anomaly was required to invert the data and generate the data quality review and inversion results graphics on our field laptop computer. For the MP system, two data sets are collected for each anomaly, as discussed in Section 6.3.4. The time includes inverting both data sets individually and then jointly, so that all three sets of results can be evaluated. Including this, the average analysis time amounted to 5 min per anomaly. As a result of lessons learned from this undertaking, we expect the average analysis time for future field runs to be less than that obtained here.

4.4 OBJECTIVE: EASE OF USE

This objective represents an opportunity for all parties involved in the data collection process, especially the data collection team, to provide feedback in areas where the process could be improved.

4.4.1 Data Requirements

Discussions with the entire field team and other observations were used.

4.4.2 Results

This objective was successfully met. Based on operator feedback, there were no significant limitations to the efficient use of either system in the field. Several suggestions were made for additional improvements to the data collection software. These improvements have since been incorporated.

4.5 OBJECTIVE: RELIABILITY

This objective captures the readiness of the system for live site demonstrations as an integrated system.

4.5.1 Data Requirements

The number of operational hours per day and the frequency of significant technical issues were collected from the demonstration field logs.

4.5.2 Results

This objective was successfully met for both systems. No significant downtime was caused by system failures. Two issues related to heat loading of the electronics package were uncovered during the August 2010 demonstration. Taken together, these issues led to Tx instabilities. Hourly rotation of ice packs placed on the electronics cover alleviated the problem. With the increased data collection tempo for the HH sensor (40 measurements per anomaly, versus eight for the MP system), the situation was only further aggravated. Since these demonstrations, these issues have been addressed and ice packs are no longer required.

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5.0 SITE DESCRIPTION

For each of these projects, one demonstration was conducted at the APG Standardized UXO Test Site located at the APG, MD. The MP system was demonstrated in August 2010 and the HH sensor in October 2010. The site description for APG is given in Section 5.1. The MP system participated in a pair of small-scale demonstrations at the Remington Woods site in October 2008 and August 2009. In May 2010, the MP system made measurements on 107 anomalies in the Dalecarlia Woods site. Site descriptions for the Remington Woods and the Dalecarlia Woods sites are available in Reference 2.

5.1 APG STANDARDIZED UXO TEST SITE

5.1.1 Site Selection

The APG site is located close to our base of operations in southern Maryland and therefore minimizes the logistics costs of deployment. Use of this site allows us to receive validation results from near-real-world conditions without incurring the logistics and intrusive investigation expenses that would be required for a demonstration at a live site.

5.1.2 Site History

The Standardized UXO Test Site is adjacent to the Trench Warfare facility at the APG. The specific area was used for a variety of ordnance tests over the years. The data from initial magnetometer and EMI surveys conducted by the MTADS team were used for a final cleanup of the site prior to the emplacement of the original test items. Prior to the two subsequent reconfiguration events, unexplained anomalies identified by demonstrators using the site were also investigated and removed.

5.1.3 Site Topography and Geology

According to the soils survey conducted for the entire area of APG in 1998, the test site consists primarily of Elkton Series type soil [6]. The Elkton Series consists of very deep, slowly permeable, poorly drained soils. These soils formed in silty aeolin sediments and the underlying loamy alluvial and marine sediments. They are on upland and lowland flats and in depressions of the Mid-Atlantic Coastal Plain. Slopes range from 0 to 2%.

Overall, the demonstration site is relatively flat and level. There are some low-lying areas in the northwest portion of the site that tend to have standing water during the wet periods of the year. The current sensor systems are moderately weatherproofed, but we did not operate them through standing water. Anomalies that were located underwater or nearby to water at the time of the survey were deferred until the end of the survey and were interrogated by carefully, if less efficiently, maneuvering the array into position. A small number of the calibration area items remained under a sufficient depth of water to be rendered inaccessible to the HH sensor throughout the demonstration.

5.1.4 Munitions Contamination

The area currently occupied by the UXO site has seen an extensive history of munitions use. Historical records provided by ATC and previous remediation results indicated that the likely munitions of interest for this site were:

- Grenades, MkI, MkII, and French V-B rifle without chute
- 3-inch Stokes (smoke and high explosive [HE])
- Grenades, French V-B rifle with chute
- 105 mm projectiles
- 60 mm mortars (including 2-inch smoke)
- 155 mm projectiles

5.1.5 Site Geodetic Control Information

There are two first-order points on the site for use as Global Positioning System (GPS) base station points. Their reported coordinates are listed in Table 2. The horizontal datum for all values is NAD83. The vertical control is referenced to the NAVD88 datum and the Geoid03 geoid. All anomaly list locations for the APG demonstrations were flagged by APG geodetics personnel using their standard techniques.

Table 2. Geodetic control at the APG standardized UXO test site.

ID	Latitude	Longitude	Elevation	Northing	Easting	HAE
477	39º 28' 18.63880" N	76º 07' 47.71815"W	10.669 m	4,369,749.013	402,810.038	-22.545
478	39º 28' 04.24219" N	76º 07' 48.50439"W	11.747 m	4,369,305.416	402,785.686	-21.473

5.1.6 Site Configuration

Figure 4 is a map of the Standardized UXO Technology Demonstration Site at APG. The calibration and blind grids are shown along with the various open field areas.

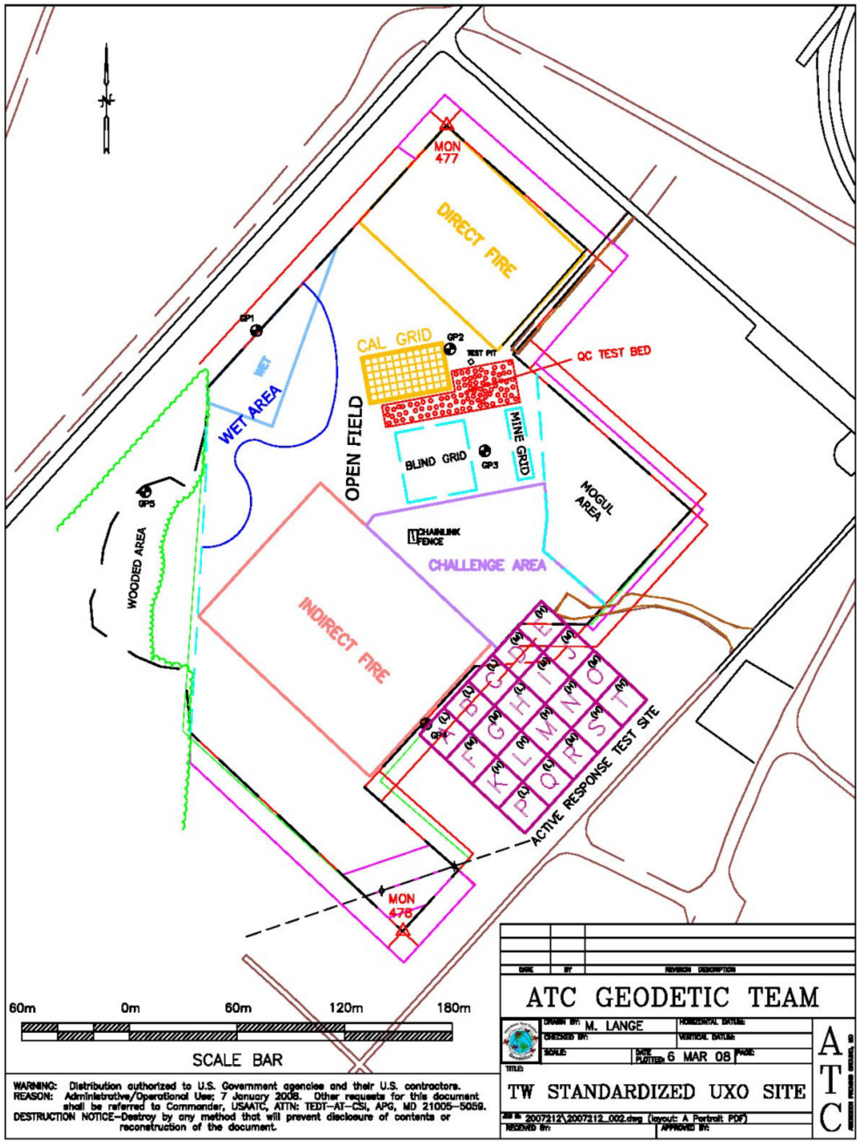

Figure 4. Map of the reconfigured APG Standardized UXO test site.

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6.0 TEST DESIGN

6.1 CONCEPTUAL EXPERIMENTAL DESIGN

Each demonstration was designed to be executed in two stages. The first stage was to characterize the response of the sensor system with respect to the items of interest and to the site-specific geology. Characterization of the sensor response was conducted at our home facility using both test stand and test field measurements prior to deployment. The background response of the demonstration site, as measured by the sensor systems, was characterized throughout data collection.

The second stage of each demonstration was a survey of the demonstration site using the specified sensor system. The target list for each demonstration was developed from previously acquired geophysical data analysis. The system (or template) was positioned roughly over the center of each anomaly on the source anomaly list and a data set collected. Each data set was then inverted using the data analysis methodology discussed in Section 7.0, and estimated target parameters were determined.

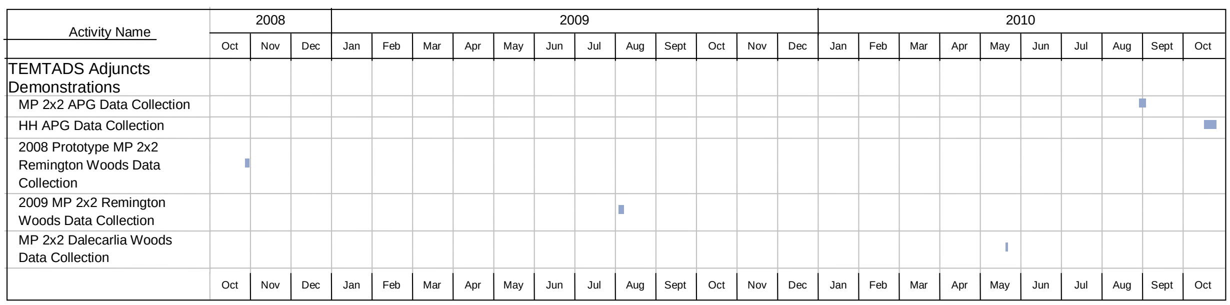

Figure 5. Schedule of field testing activities.

6.2 SITE PREPARATION

Basic facilities such as portable toilets and field buildings were provided. Secure storage for the sensor systems was available in the field buildings on site. Site personnel placed plastic pin flags with the flag number clearly marked at each flag position using their standard techniques prior to each demonstration.

6.3 SYSTEMS SPECIFICATION

These demonstrations were conducted using the NRL TEMTADS HH Sensor and the TEMTADS MP 2x2 Cart.

6.3.1 TEMTADS Electronics

The Tx electronics and the data acquisition computer are mounted in the operator backpack, as shown in Figure 6 (left). Custom software written by NRL provides data acquisition functionality. After the sensor/array is positioned roughly centered over the center of the

anomaly, the data acquisition cycle is initiated. Each Tx is fired in a sequence. The received signal is recorded for all Rx channels for each transmit cycle. The transmit pulse waveform duration is 2.7 s. While it is possible to record the entire decay transient at 500 MHz, we have found that binning the data into 122 time gates simplifies the analysis and provides additional signal averaging without significant loss of temporal resolution in the transient decays [7]. The data are recorded in a binary format as a single file with multiple data points (one data point per Tx cycle). The file name corresponds to the anomaly ID from the target list under investigation.

Figure 6. TEMTADS 2x2 electronics backpack (left) and TEMTADS MP 2x2 cart and data acquisition operators (right).

6.3.2 Data Acquisition User Interface

The data acquisition computer is mounted on a backpack worn by one of the data acquisition operators. The second operator controls the data collection using a personal data assistant, which wirelessly (IEEE 802.11b) communicates with the data acquisition computer. The second operator also manages field notes and team orienteering functions. Data collection with the MP system at the former Camp Beale, CA, is shown in Figure 6 (right).

6.3.3 TEMTADS Hand-Held Sensor System

The HH sensor is deployed on a raised wooden template positioned over each target in turn, resulting in a sensor-to-ground offset of up to 25 cm. The optimum sensor height is dependent on the background ground response and is determined on a site-by-site basis. A series of 40 individual measurements is then made using the template as a precise guide for relative location. For each measurement, the system activates the Tx and collected decay data from the Rx coil. The sensor is then moved to each template position in turn, and the next set of data is collected. In addition to the positions on the template, in-air and near-surface background locations are included as shown schematically in Figure 7 (right). An example of the in-air measurement is shown on the cover of this document. The position numbering on the schematic indicates the recommended order of collection.

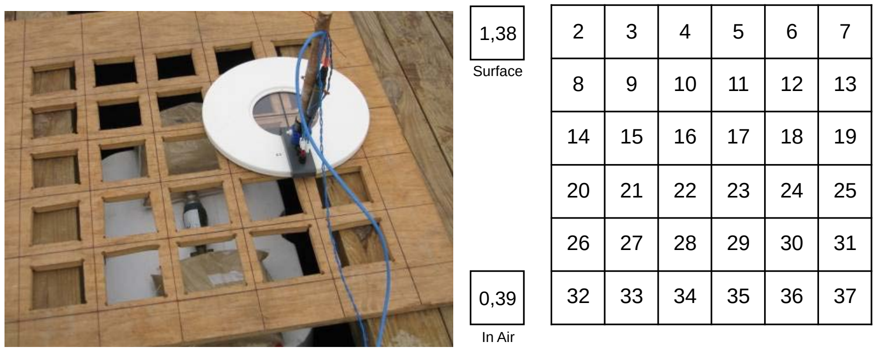

Figure 7. The position template over a test article (left) and shown schematically (right).

The complete set of data for each target is then inverted for target characteristics. The HH sensor deployed at APG is shown in Figure 8. At this point in the project, the system operates in a cued mode only and there is no facility for a search mode to reacquire the anomaly prior to cued data collection. The locations of the anomalies must already be known and flagged for reacquisition. In the future, the system will be evaluated using localized positioning systems to speed up the acquisition time as compared to using the wooden template.

Figure 8. The NRL TEMTADS hand-held sensor.

6.3.4 TEMTADS MP 2x2 Cart

The MP system consists of four EMI sensors developed for the NRL TEMTADS 5x5 array arranged in a 2x2 array, as shown schematically in Figure 9. The MP system, shown in Figure 10 at APG, is fabricated from PVC plastic and G-10 fiberglass. The center-to-center distance is 40 cm yielding an 80 cm x 80 cm array. The array is deployed on a set of wheels, resulting in a sensor-to-ground offset of approximately 25 cm. At this point in the project, the system operates in a cued mode only.

The locations of the anomalies must already be known and flagged for reacquisition. In the future, the system will be equipped with GPS or other positioning systems and be able to operate in a detection mode. The MP system is positioned roughly centered over each target flag. Once positioned, data are collected while firing each Tx in sequence.

In previous testing [8], we found demonstrable value in collecting a second set of data at a location approximately 20 cm (1/2 a sensor width) off the anomaly center, particularly for deeper targets. This process was continued for these demonstrations. Analyses of the results with and without this second data set were included in our assessment of the performance of the MP system. See Reference 2 for further details.

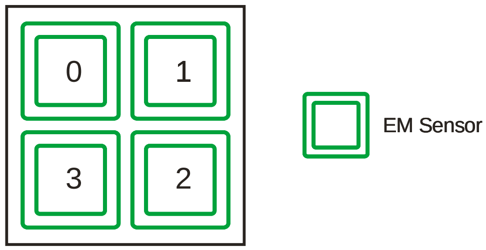

Figure 9. Sketch of the TEMTADS MP 2x2 sensor array showing the position of the four sensors. The standard MR-200601 sensors are shown schematically.

Figure 10. The NRL TEMTADS 2x2 man-portable cart.

6.4 DATA COLLECTION PROCEDURES

6.4.1 Scale of the Demonstrations

The HH sensor demonstration was conducted at the APG Standardized UXO test site. The calibration area and the blind grid areas were surveyed. Only those cells in the blind grid area that were on the union of the TEMTADS (MR-200601) and SAINT (MR-200810) target lists were surveyed with the HH sensor. The MP system demonstration at the same site covered the calibration area, and the blind grid and indirect fire areas, using the original TEMTADS target list. The Remington Woods and Dalecarlia Woods demonstration were conducted on the respective sites using provided target lists from the ongoing remediation efforts. For all sites, the locations on the target lists were previously reacquired and flagged.

6.4.2 Sample Density

The EMI data spacing for the MP system is fixed at 40 cm in both directions by the array design. Two sets of data were collected for each flag position, as described in Section 6.3.4. The HH sensor data are collected on a 6x6 grid template with 15 cm grid spacing. In-air and ground

background measurements are taken on a known quiet spot within a few steps of the flag location.

6.4.3 Quality Checks

Two data quality checks were performed on the EMI data. After background subtraction, the data were plotted as a function of time for each Tx/Rx pair. An example plot is shown in Figure 11 for the MP system and APG calibration area item G002, a 37 mm projectile buried at a depth of 24 cm below the surface. The plots were visually inspected to verify that there was a well-defined anomaly without extraneous signals or dropouts. Further QC evaluation on the transmit/receive cross terms was based on the dipole inversion results. An example of the inversion results (principal polarizability decays) is shown in Figure 12 for the data shown in Figure 11. Our experience has been that data glitches show up as a degraded match of the extracted response coefficients to the reference values, when appropriate. This is quantitatively seen as a reduced fit coherence. The fit coherence is a value (0–1) reflecting how well the fit result response coefficients reproduce the collected data. Qualitative evaluation is also conducted by visual inspection of several QC plots by the data analyst.

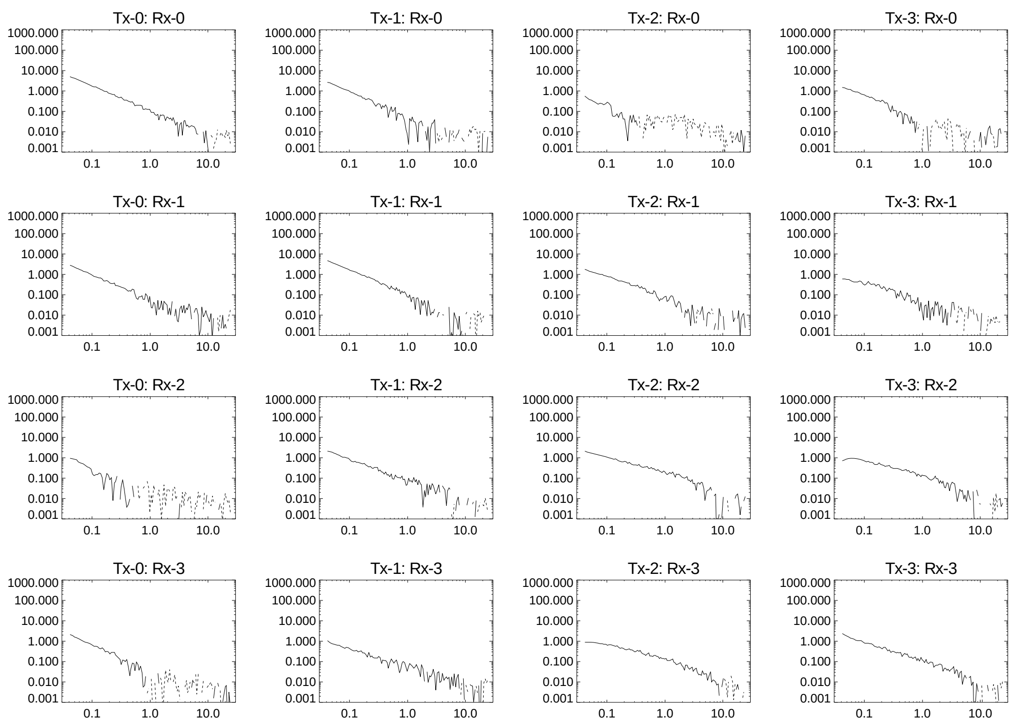

Figure 11. TEMTADS MP 2x2 cart QC plot for APG calibration area item G002, a 37 mm projectile at a depth of 24 cm below the surface.

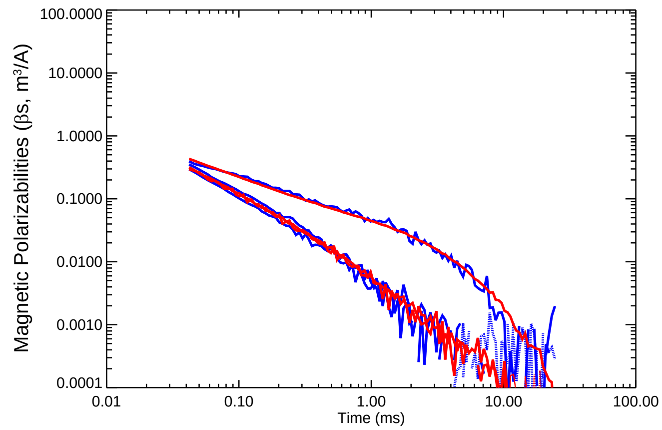

Figure 12. TEMTADS MP 2x2 cart derived response coefficients for APG calibration area item G002, a 37 mm projectile at a depth of 24 cm below the surface.
The blue lines are the fit results for the collected data, and the red lines indicate a library entry for a 37 mm projectile.

Any data set deemed unsatisfactory by the data analyst was flagged and not processed further. The anomaly corresponding to the flagged data was logged for re-acquisition by the field team.

6.4.4 Data Summary

The primary performance metrics for these demonstrations were the classification performance results for the two systems at the APG Standardized UXO test site. The performance results are provided by the site managers after the classification rankings are submitted [3,4]. The ground truth of this site is held by the principal investigators (PIs) and the results are discussed in Section 4.1 in aggregate. See Reference 2 for more details. Both the Dalecarlia and Remington Woods demonstrations were conducted as innovative technology demonstrations as part of ongoing efforts at each site. Each anomaly investigated as part of these demonstrations was intrusively investigated by the site team after data collection. Once a prioritized diglist was submitted, the full ground truth was released to us for post-mortem evaluation. The results are discussed in Reference 2.

6.5 VALIDATION

Validation of the performance of these technologies comes primarily from comparison of the classification results of the data analysis to the ground truth. In the case of the APG Standardized UXO test site, the ground truth is known to the site managers and no intrusive investigation is required. For the Remington Woods and Dalecarlia Woods sites, the targets selected for investigation were already scheduled for intrusive investigation as part of the ongoing cleanup efforts at each site. Ground truth results were provided after the intrusive investigations were complete. Further details on the validation process are presented in Reference 2.

7.0 DATA ANALYSIS AND PRODUCTS

7.1 PREPROCESSING

7.1.1 TEMTADS Hand-Held Sensor

The HH sensor has one EMI sensor with concentric Tx and Rx coils. For each transmit pulse, we record the transient decay response at the Rx (12,500 points). The recorded data are then binned into a series of time gates for improved manageability and increased signal-to-noise. Normally we use 122 logarithmically spaced time gates. In preprocessing, the recorded signals are normalized by the Tx currents to account for any Tx variations. On average, the peak Tx current is approximately 7.5 Amps. Decay time is measured from the time that Tx turn-off is initiated. We subtract 0.028 ms from the nominal gate times to account for the time delay due to effects of the receive coil, electronics, and the Tx turn-off delay [9]. The correction was determined empirically by comparing measured responses for test spheres with theory. Measured responses include interfering signals due to Tx ringing and related artifacts out to about 0.160 msec. Consequently, we only include response beyond 118 μs in our analysis as the background is too large and varying to be reliably subtracted at earlier times. This leaves 99 gates spaced logarithmically between 0.118 ms and 25.35 ms.

The background response is subtracted from each target measurement using data collected in a nearby target-free region measured at the same height as the template. All background measurements were intercompared to evaluate background variability and identify outliers which may correspond to measurements over nonferrous targets. Changes in moisture content and outside temperature have been shown to cause variation in the backgrounds, necessitating care when collecting data after weather events such as rain.

7.1.2 TEMTADS MP 2x2 Cart

The MP system has four sensor elements, each consisting of a Tx coil and a vertically oriented Rx coil. For each transmit pulse, the responses at all the Rx are recorded. This results in 16 possible Tx/Rx combinations in the data set (4 Tx x 4 Rx cubes). In preprocessing, the recorded signals are normalized by the peak Tx current in a similar manner as for the HH sensor. Although the data acquisition system records the signal over 122 logarithmically spaced time gates, the measured responses over the first seven gates include interfering signals due to Tx ringing and related artifacts and are discarded. This leaves 115 gates spaced logarithmically between 0.042 ms and 25.35 ms.

The background response is subtracted from each target measurement using data collected at a nearby target-free background location. As few measurement cycles are required for the MP system (8 versus 40), the MP system can collect data over more targets/hour than the HH sensor for a given set of data acquisition parameters. Based on previous experience with the MP system and the TEMTADS 5x5 array, a background measurement for the MP system was made approximately every 30 minutes. The same caveats mentioned in the previous section apply.

7.2 TARGET SELECTION FOR DETECTION

7.2.1 Aberdeen Proving Ground, MD

The anomaly list for the blind grid and the indirect fire areas were the same ones as used for the TEMTADS 5x5 array demonstration in June 2008 [10].

7.2.2 Remington Woods, CT

DuPont and URS Corporation are currently involved in an ongoing UXO remediation effort at this site. The initial target detection is based on the results of an EM61-MK2 survey. See Reference 2 for further details.

7.2.3 Dalecarlia Woods, DC

The USACE, Baltimore District has an established, ongoing remediation project at the Spring Valley FUDS. A small segment of the dig list for 2010 was selected for investigation based on schedule. See Reference 2 for further details.

7.3 PARAMETER ESTIMATION

The raw signature data from TEMTADS sensors reflect details of the sensor/target geometry as well as inherent EMI response characteristics of the targets themselves. In order to separate out the intrinsic target response properties from sensor/target geometry effects, we invert the signature data to estimate principal axis magnetic polarizabilities for the targets. The TEMTADS data are inverted using the standard induced dipole response model wherein the effect of eddy currents set up in the target by the primary field is represented by a set of three orthogonal magnetic dipoles at the target location [11]. The measured signal is a linear function of the induced dipole moment **m**, which can be expressed in terms of a time dependent polarizability tensor **B** as

$$\mathbf{m} = \mathbf{U}\mathbf{B}\mathbf{U}^{T}\cdot\mathbf{H}_0$$

where **U** is the transformation matrix between the physical coordinate directions and the principal axes of the target and $\mathbf{H}_0$ is the primary field strength at the target. The eigenvalues $\beta_i(t)$ of the polarizability tensor are the principal axis polarizabilities.

Given a set of measurements of the target response with varying geometries or “look angles” at the target, the data can be inverted to determine the local (X,Y,Z) location of the target, the orientation of its principal axes (ϕ,θ,ψ), and the principal axis polarizabilities (β_1, β_2, β_3). The set of nine fit parameters (X,Y,Z, (β_1, β_2, β_3) that minimize the difference between the measured responses and those calculated using the dipole response model are searched for. Since the system currently does not know or record the sensor location or orientation, target location and orientation are known well locally but are not well georeferenced.

Figure 13 shows an example of the principal axis polarizabilities determined from TEMTADS array data. The target, a mortar fragment, is a slightly bent plate about 0.5 cm thick, 25 cm long,

and 15 cm wide. The red curve is the polarizability when the primary field is normal to the surface of the plate, while the green and blue curves correspond to cases where the primary field is aligned along each of the edges.

Not every target on the target list exhibited a strong enough TEM response to support extraction of target polarizabilities. All the data were run through the inversion routines and the results manually screened to identify those targets that could not be reliably parameterized. Several criteria were used: signal strength relative to background, dipole fit error (difference between data and model fit to data), and the visual appearance of the polarizability curves.

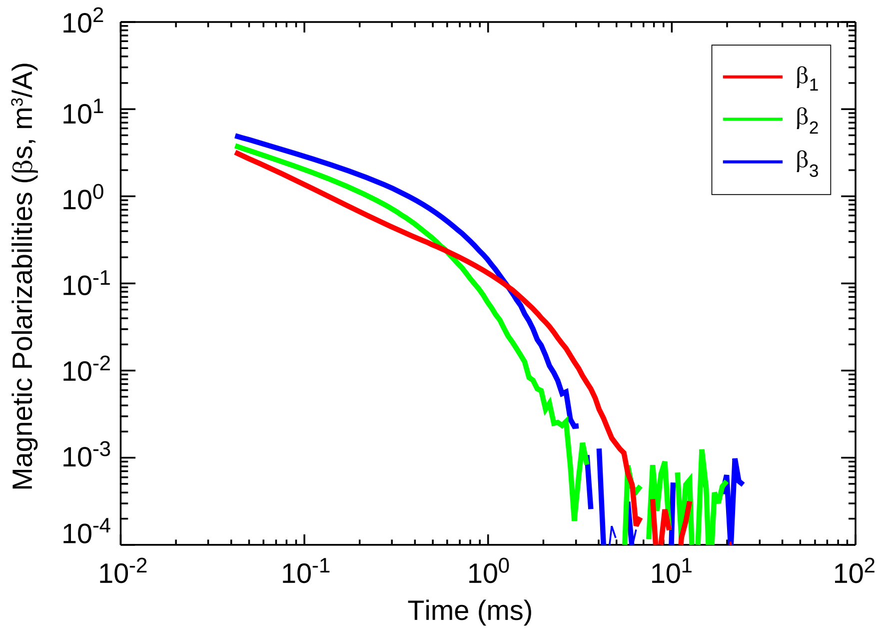

Figure 13. Principal axis polarizabilities for a 0.5 cm thick by 25 cm long by 15 cm wide mortar fragment.

7.4 CLASSIFIER AND TRAINING

Target classification is based on a library matching procedure whereby we compare the quality of both an unconstrained dipole inversion of the TEM array data and the ratio ρ. The ratio ρ is defined as the ratio of the quality of an unconstrained dipole fit of the TEM data to the quality of a dipole fit constrained by principal axis polarizabilities drawn from the signature library. Fit quality is the squared correlation coefficient between the model fit and the data. If ρ is equal to one, then the library item is as good a match to the data as possible. If the value of ρ is small, then the library item is a poor match. For the unconstrained inversion, we utilize an algorithm that compares our derived polarizabilities with a library of known target signatures. The match is based on these criteria: the amplitude of the primary polarizability, and the ratio of the second and third polarizabilities to the first. We have computed match metrics, each of which runs from 0 (terrible match) to 1 (perfect match).

Our experience with these sensors has been that principal polarizabilities determined from in-air measurements are indistinguishable from those determined from measurements taken over buried

targets. We have an extensive collection of inert military munitions collected from many sources that were measured at our home facility using the TEMTADS family of sensors mounted on a test stand. We have also assembled a fairly extensive polarizability database for clutter items recovered from several different sites. These data collections were used as training data for establishing UXO/clutter discrimination boundaries on the coherence ratio ρ and on the direct comparison metric.

7.5 DATA PRODUCTS

The data analysis products generated were specifically tailored for the requirements of each demonstration site. Further details and the presentation formats can be found in Reference 2.

8.0 PERFORMANCE ASSESSMENT

For the TEMTADS family of sensors, a significant amount of data has been previously collected on test stands and under field conditions at our test field [12] and during our recent demonstrations at APG [5,8]; San Luis Obispo (SLO) [13]; Bridgeport, CT [8]; and at the former Camp Butner, NC [14]. These data and the corresponding fit parameters provide us with a set of reference parameters including those of clear background (i.e., no anomaly present). Examples of the types of analyses that are typically conducted are given in the following sections.

8.1 DAILY CALIBRATION ACTIVITIES

Daily calibration efforts consisted of collecting background (no anomaly) data sets periodically throughout the day and during the demonstrations. The background (no anomaly) data sets were collected at known quiet spots to monitor the system noise floor and for background subtraction of signal data.

8.1.1 Background Variability

A group of anomaly-free areas throughout each demonstration site were identified in advance from available data, MTADS magnetometer data in the case of APG, for example. For the MP system, the background variation is presented as the mean and standard deviation of the four monostatic measured signals at a decay time of 42 μs (seventh time gate). For the APG demonstration, the results for all 86 background measurements taken for the duration of the demonstration (August 30 – September 2, 2010) are shown in Figure 14. Julian date codes (day of the year) are used to label the horizontal axis. See Reference 2 for MP results from the Remington Woods, CT, and Dalecarlia Woods, DC, sites and HH results from APG.

These variations have been correlated in the field with both ambient temperature and the moisture level in the soil surface and vegetation. Background levels tend to be high in the morning, and on a typical field day, the mornings are cool and dew or frost may be present on the ground. As seen in Figure 14 on Julian dates 243 and 244 and in Reference 14, as the day progresses the background level tends to decrease, which correlates with increased ambient temperature as well as evaporation of any moisture. It is possible that this effect is caused by changes in the coil impedances associated with changing temperature and/or humidity. However, we cannot rule out soil and vegetation conductivity effects on the background signal. Moisture alone can cause an increased background value, as was seen in Reference 14 on July 17, 2010. During rain events, the background level could double rapidly and would recover on the hour time scale.

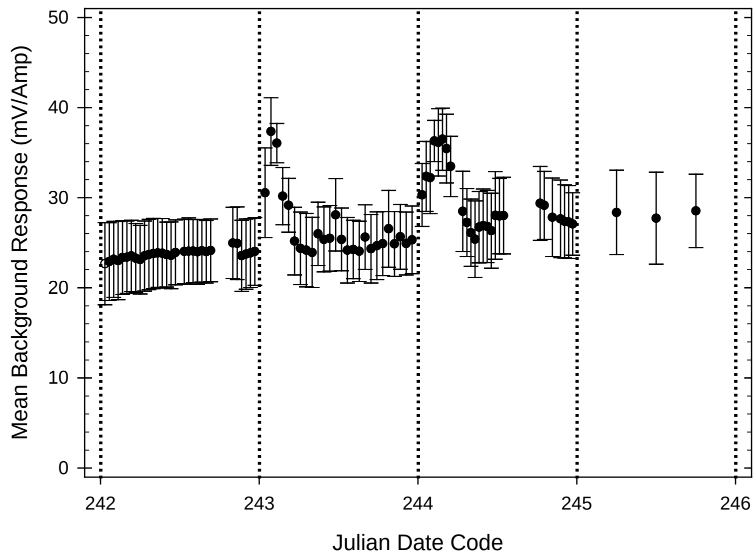

Figure 14. Intra- and inter-daily variations in the response of the MP system to background anomaly-free areas at a time gate of 42 μs through the duration of the demonstration at APG.

8.1.2 Performance at APG – 60 mm Mortars

For recent live site demonstrations, the day-to-day performance of a technology is demonstrated through the use of an instrument verification strip (IVS). The intent of an IVS is to provide the ability to verify the repeatability of the system response on several examples of items of interest. The APG Standardized UXO test site has a previously emplaced, large (66-item) calibration area for demonstrators to use and a single, shallow pit for placing other objects. As such, demonstrations at APG measure the calibration area items a single time prior to moving on to the blind grid and open field areas. Therefore to demonstrate the day-to-day variability of the recovered parameters for each of the sensor technologies, the results for a single munitions type are monitored in aggregate for each system. Except for the calibration area, the ground truth is held close at ATC and not available to the demonstrators. Items believed to be 60 mm mortars are used in the following example. No IVS-like facilities were available at Remington Woods, or Dalecarlia Woods so no such comparisons were made.

The analysis results for the HH sensor are shown in Figure 15. The fit-result principal magnetic polarizabilities are shown in black, red, and green, respectively. The mean and a 2σ envelope for the axial and transverse polarizabilities are shown in magenta and blue, respectively. The HH system's performance was quantitatively similar to that of the full TEMTADS 5x5 array, as seen in Reference 2. The analysis results for the MP system are presented in Reference 2. The performance of the MP system was found to be significantly degraded. See Section 8.2 for further discussion of the MP system performance.

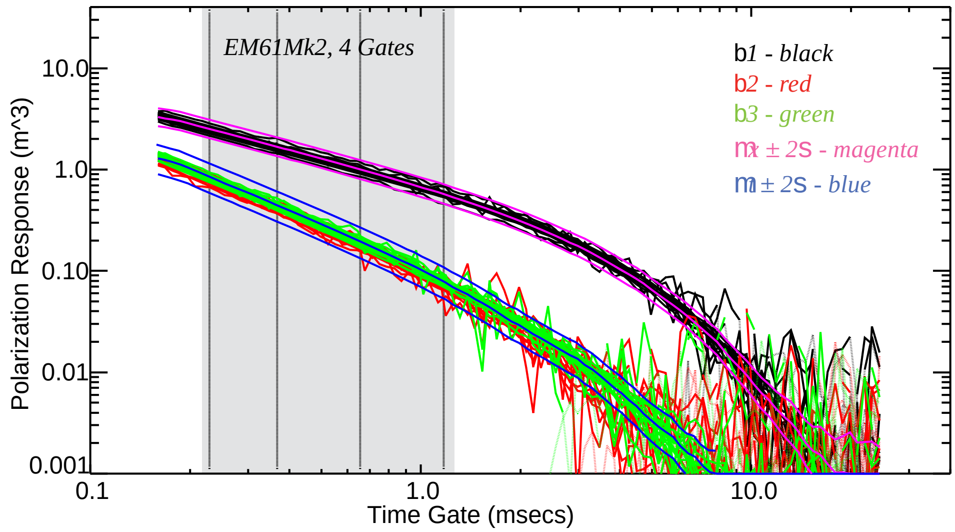

Figure 15. TEMTADS hand-held sensor derived response coefficients for all items at APG classified as 60 mm mortars.

8.2 DATA ANALYSIS IN SUPPORT OF UPGRADING EMI SENSORS TO TRI-AXIAL RECEIVERS FOR 2X2 MP CART SYSTEM

As was seen in Section 4.1, the performance of the MP system has been disappointing to date. SNRs for the MP system and 5x5 array do not appear to be sufficiently different to account for the difference in performance between the two systems. See Reference 2 for further discussion. We use a standard dipole inversion procedure to estimate the principal axis polarizabilities. How well the parameters can be estimated depends on the noise in the measurements and the shape of the fit error surface. At a given noise level, a sensor that produces an error surface with a sharp minimum is better able to constrain uncertainty in the target parameter than one that has a broad, flat region around the minimum error. The shape of the error surface depends on both what the sensor is measuring (i.e., the target parameters) and how it is doing the measuring (data density and extent, transmit and receive coil configurations, etc.). A simple example serves to illustrate the basic difference between the MP system and the 5x5 array. Figure 16 shows cuts through the error surfaces for the MP system and the 5x5 array as functions of horizontal distance from the target location along the minimum curvature direction. All other parameters are fixed at their true values. The target is axially symmetric with 3⅓ to 1 polarizability ratio and is directly under the array, aligned with long axis horizontal and parallel to the cross-track direction (i.e., perpendicular to the 20 cm step for the MP system). The different plots are for different target distances below the sensors, as indicated. For a target at 25 cm (on the surface for the MP system, whose sensors ride 27 cm above the ground), the error cuts are similar. For progressively deeper targets, the MP system error surface broadens out more and more relative to the error surface for the 5x5 array. The chain-dashed curves show what happens if the standard single axis MP system Rx coils are replaced with three component vector Rxs, and we forego the second (stepped) measurement. The additional information from the horizontal components of the induced field at the Rxs is able to better constrain the inversion, and the error surface is sharpened significantly for deeper targets.

Based on these results, the recommendation to replace the original TEMTADS sensors in the MP system with the TEMTADS/3D sensors was made to the ESTCP Program Office in the winter of 2010. The recommendation was approved and the modifications to the system made in early 2011.

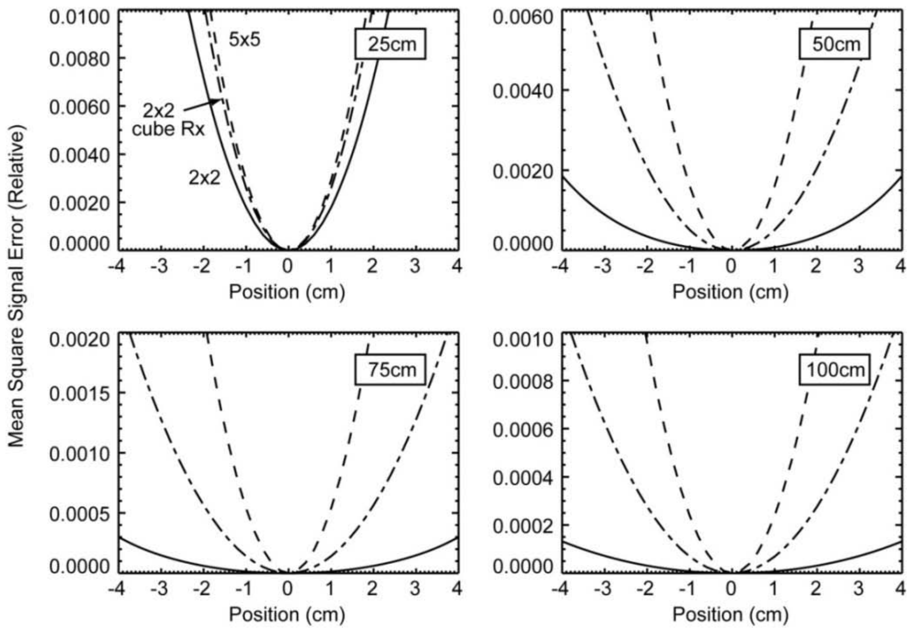

Figure 16. Cuts through error surface for 2x2 array (solid lines) and 5x5 array (dashed lines) for targets 25 cm, 50 cm, 75 cm, and 100 cm below the array.

Chain dashed curves show effects of replacing 2x2 receiver coils with tri-axial receiver cubes.

9.0 COST ASSESSMENT

9.1 COST MODEL

The cost elements that were tracked for the APG demonstrations are detailed in Table 3 and Table 4. The provided cost elements are based on a model recently developed for the MP system at Camp Beale in 2011 [15]. Table 3 contains the cost model for the HH sensor and Table 4 the cost model for the MP system. While neither system is currently commercially available, an estimated daily rental rate is provided for comparison to other technologies. The rental rate is based, in part, on the costs of items purchased in prototype quantities (single units) and would presumably decrease significantly if the items were procured at production quantity levels.

9.2 COST DRIVERS

Two factors were expected to be strong drivers of cost for this technology as demonstrated. The first is the number of anomalies that can be surveyed per day in a cued mode. Higher productivity in data collection equates to more anomalies investigated for a given period of time in the field. The time required for analyzing individual anomalies can be significantly higher than for other, more traditional methods and could become a cost driver due to the time involvement. As shown in Section 4.3, with trained data analysts, the analysis time per anomaly is already comparable to the data collection time. The thoughtful use of available automation techniques for individual anomaly analysis with operator QC support can further moderate this cost driver.

9.3 COST BENEFIT

The ability to reduce the number of nonhazardous items that have to be dug or have to be dug as presumptively hazardous items directly reduces the cost of a remediation effort. The additional information for anomaly classification provided by these sensor systems provides additional information for the purposes of anomaly classification. If there is buy-in from the stakeholders to use these techniques, this information can be used to reduce costs.

To demonstrate the potential cost benefit of using this technology on an actual cleanup, an example scenario is presented. The demonstrations discussed in this report were of short duration with a small number of anomalies to capitalize mobilization costs. Therefore, we will consider a larger effort where only the field work and data analysis costs for the classification effort are significant. Costs for intrusive investigations of the anomalies are also considered.

To estimate the cost per anomaly for collecting a cued data set and the required data analysis to reach a UXO/clutter classification decision, the data presented in Table 3 and Table 4 are used for the HH sensor and MP system, respectively. Estimated data collection costs/anomaly for the HH sensor and MP system were determined to be $59 and $18/anomaly, respectively.

Table 3. TEMTADS hand-held sensor tracked costs.

Cost Element	Data Tracked	Cost
Data Collection Costs		
Pre/post survey activities	Component costs and integration costs • Spares and repairs	 $3500
	Cost to pack the array and equipment, mobilize to the site, and return • Personnel required to pack • Packing hours • Personnel to mobilize • Mobilization hours • Transportation costs	$9400 1 8 3 8 $6000
	Cost to assemble the system, perform initial calibration tests • Personnel required • Hours required	$195 3 0.5
Survey costs	Unit cost per anomaly investigated. This will be calculated as daily survey costs divided by the number of anomalies investigated per day. • Equipment rental (day) • Daily calibration (hours) • Survey personnel required • Survey hours per day • Daily equipment breakdown and storage (hours)	**$36.90 / anom.** $145 0.2 2 8 0.5
Processing Costs		**$21.65 / anom.**
Preprocessing	Time required to perform standard data cleanup and geophysical data QC	10 min / anom.
Parameter estimation	Time required to extract parameters for each anomaly	2 min / anomaly

These costs are based on an assumed median salary of $5200 per week per person while in the field. A field crew of two persons for data collection and one data analyst are presented as appropriate for a trained and experienced commercial crew. Factoring in time for daily setup, breakdown, and IVS work, one can expect to achieve real-world production rates of roughly 80% of those achieved during the APG demonstrations. As a result, production rates of 55 and 260 anomalies/day for the HH sensor and the MP system, respectively, are considered.

The cost of fielding an appropriately certified UXO dig team, without mobilization costs, can range between $37,000 and $50,000 per week (FY 2010 dollars). Assuming that the team can clear between 310 and 420 anomalies a day, the cost to dig an anomaly is $90–160/anomaly.

Table 4. TEMTADS MP 2x2 cart tracked costs.

Cost Element	Data Tracked	Cost
Data Collection Costs		
Pre/post survey activities	Component costs and integration costs • Spares and repairs	 $3500
	Cost to pack the array and equipment, mobilize to the site, and return • Personnel required to pack • Packing hours • Personnel to mobilize • Mobilization hours • Transportation costs	$12,450 1 16 3 8 $7250
	Cost to assemble the system, perform initial calibration tests • Personnel required • Hours required	$780 3 2
Survey costs	Unit cost per anomaly investigated. This will be calculated as daily survey costs divided by the number of anomalies investigated per day. • Equipment rental (day) • Daily calibration (hours) • Survey personnel required • Survey hours per day • Daily equipment breakdown and storage (hours)	**$7.15 / anom.** $190 0.5 2 8 0.5
Processing Costs		**$10.85 / anom.**
Preprocessing	Time required to perform standard data cleanup and to merge the location and geophysical data	3 min / anomaly
Parameter estimation	Time required to extract parameters for all anomalies	2 min / anomaly

Assuming that 1% of the items dug are in fact UXO, the remediation of those UXO must be accounted for. Including a remediation cost of $1000/UXO, the average cost per dig would range from $100–170/anomaly.

Two examples are considered assuming a hypothetical cleanup site with 10,000 anomalies to be cleared, one based on using the HH sensor for classification and one based on using the MP system. Using the above analysis, the cost of the cleanup with all anomalies dug would range from $1 million to $1.7 million total. In both cases, one assumes that the TEMTADS Adjuncts classify the measured anomalies sufficiently well to reduce the number of actual digs required to 10% of the original number. With this classification accuracy, only 1000 anomalies would require intrusive investigation. Of those 1000 anomalies, it is assumed that 1% would be a UXO, requiring the $1000/UXO remediation cost listed above. Net savings are presented below as the difference in cost between intrusively investigating all anomalies without a classification effort and of a classification effort followed by intrusive investigation of 10% of the original anomaly count, or 1000 anomalies.

For the TEMTADS MP 2x2 cart system, the combined cost of the TEMTADS survey and the resultant digging drops from a range of $1 million to $1.7 million to a range of $278,300 to $350,000, or a potential savings of 72–79%. Even with the lower production rate of the HH sensor, the costs drop from a range of $1 million to $1.7 million to a range of $683,800 to $755,500, or a potential savings of 30–56%.

10.0 IMPLEMENTATION ISSUES

The goal of these projects was to design and field units more amenable to operation in increasingly confined terrain and topology. This was to be accomplished by implementing MP and HH configurations with the same UXO classification performance as the larger, vehicle-towed NRL TEMTADS. The MP configurations could also be adapted for vehicle-towed configurations using smaller, simpler tow vehicles. A second goal was to transition these technologies from being research prototypes to being usable in the industrial community where appropriate. The mechanics of collecting classification-grade EMI data with these systems has been shown to be fairly routine in the research community.

As part of the ESTCP Munitions Response Live Site Demonstrations, industrial partners will be exposed to the MP system and the associated data collection and processing procedures. The success of this effort will be evaluated on an ongoing basis through the Live Site demonstrations. Analysis of data from these systems remains somewhat of a specialty, requiring specific software and knowledge to proficiently conduct. The successful transition of the TEMTADS 5x5 array data QC/analysis process to the Geosoft Oasis montaj environment provides a clear pathway for resolving these issues. A final implementation issue is that a clear path to making the TEMTADS Adjuncts commercially available has not been identified yet. Discussions with various groups along these lines are ongoing.

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